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Jupiter's Magnetic Tail: Voyager 1

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ABSTRACT

Magnetic field observations by the Voyager 1 spacecraft during the outbound traversal of the Jovian magnetosphere in March 1979 suggest the detection of an extended magnetic tail, which has been formed by the solar wind interaction with the planetary field. The apparent diameter of the tail is 300-400 R_J but its length is not measured. When combined with the GSFC O_4 model of the planetary field, this magnetosphere topology leads to polar cap auroral zones approximately 20° in diameter, considerably smaller than Earth's. The northern zone is found to be highly eccentric, encircling neither the rotational pole nor the magnetic pole of Jupiter, and limited to System III (1965) longitudes $\sim 133^{\circ}$ to 190° and latitudes $\sim 62^{\circ}$ - 82°.

INTRODUCTION

In March 1979, Voyager 1 became the third spacecraft to penetrate and study in situ the magnetosphere of Jupiter. Earlier observations and interpretations from Pioneers 10 and 11 in 1973-74 indicated the development of a magnetodisk topology describing the magnetosphere[1]. In this model, the combined effects of rapid rotation and a strong planetary magnetic field yield an equatorial region with a considerably enhanced charged particle and plasma population and distended magnetic field lines[2]. Thus, the central region of the magnetodisk effectively carries an azimuthal electrical current and this region is commonly referred to as the current sheet. Controversy arose over whether the current sheet of the magnetodisk was planar and parallel to the magnetic equatorial plane, with a spiraling of the magnetic meridian planes and field lines due to a finite Alfven speed[3], or if the current sheet and magnetodisk were distorted due to the centrifugal forces and deviated or "floppy" so as to become parallel to the Jovigraphic equatorial plane at distances greater than 20 R_J[4]. In addition, an attempt was made to interpret the data qualitatively in the framework of a "magnetic anomaly" model[5], based upon the highly asymmetric planetary field[4,6], which did not include an azimuthal current sheet.

The common feature of these earlier interpretations was that they were all based upon a planet-centered view of the processes and mechanisms which control the configuration of the outer magnetosphere. It is the purpose of this brief note to discuss the Voyager 1 experimental observations, which are most naturally interpreted in terms of a well developed magnetic tail on the nightside of the Jovian magnetosphere. This tail, with a "neutral sheet" separating the upper and lower lobes of opposite field polarity, is formed and controlled by the external forces associated with the solar wind interaction. The inner magnetosphere's current sheet is found to merge with the tail's neutral sheet. This configuration leads to a strong local time control of the outer Jovian magnetosphere configuration, in contrast to earlier models which emphasized inner, i.e. planetary, control.

OBSERVATIONS

A summary of the preliminary results obtained from the Voyager 1 magnetometer has already been presented[7]. The Voyager 1 spacecraft entered the Jovian magnetosphere at a local time of 1100 with magnetopause crossings observed at Jovicentric distances between 67 and 47 R_J and exited the magnetosphere at a local time of 0400 with magnetopause crossings occurring between 153 and 170 R_J. Characteristic current sheet-neutral sheet signatures were observed in the magnetic field data, as the spacecraft passed through the magnetosphere. They manifested themselves as significant decreases in the magnetic field intensity, occurring simultaneous with variations in the direction of the magnetic field. These are interpreted in the inner magnetosphere, $R < 30\ R_J$, as evidence for a large scale azimuthal current or a current sheet within the magnetosphere.

Within 30 R_J, these magnetically characteristic regions occurred nearly simultaneous with the crossing of the magnetic equatorial plane. Although the field intensity decreased appreciably, it never reached zero, and the variation of field direction was gradual and not consistent with the nearly anti-parallel field directions on opposite sides of the current sheet which were observed at larger radial distances. Beyond 30 R_J, the characteristics of the current sheet crossings were similar to those seen when crossing the neutral sheet in the Earth's magnetic tail: a sharply defined dip in the field intensity, to very small values, while the field direction changed by approximately 180°. Within 80 R_J, there were two sheet crossings every 10 hours, although not at a 5 hour spacing. Beyond 80 R_J, complete traversals of the current sheet were not observed as evidenced in the field direction. However, very close approaches were made, as seen in the field intensity dips and increased higher frequency fluctuations which occurred with regularity at the 10 hour rotation period of the planet. The times of the occurrence of the full traversals merged as the two traversals per rotation period changed to one partial traversal per rotation period.

Figure 1 presents a diagram of the trajectory of the spacecraft outbound from periapsis as observed in both Jovian dipole magnetic coordinates (tilt = 9.6° and System III (1965) longitude = 202°) and solar magnetospheric coordinates. This illustrates the change from planetocentric control of the occurrence of sheet crossings to solar wind control in the outer magnetosphere. In the upper part of Figure 1 it is seen that within 25 R_J, the current sheet crossings, denoted by X's, clearly occur nearly coincident with the spacecraft traversal of the magnetic equatorial plane. This is to be contrasted with the lower panel in which there is no consistency with traversal of the solar magnetospheric equatorial plane. In the outer portion of the Voyager 1 magnetosphere traversal, the magnetic dips, indicated by O's, are seen to occur during those portions of the trajectory which were near or below the solar magnetospheric equatorial plane. The dips were sometimes observed as extended periods of reduced and variable field strength. Such intervals are shown by sequences of O's. The conclusion from this figure is that the magnetospheric structure is characterised by a transition from a magnetic equatorial current sheet to the neutral sheet of the tail which is approximately parallel to the solar magnetospheric X-Y plane.

Earlier studies of the Pioneer 10 outbound trajectory had primarily emphasized the times of crossing or penetration of the current sheet[2,3]. In order to correctly understand the magnetic field observations, however, it is also important to properly consider the configuration of the magnetic field. In order to study these Voyager 1 data further, we appropriately transform the vector observations into solar magnetosphere coordinates. Figure 2 presents a projection of the hourly averaged X-Y and Y-Z components in both the X-Y and Y-Z planes along the trajectory of Voyager 1. The position of the magnetopause is included in the upper panel and was derived by matching the mid points of the inbound and outbound regions of multiple crossings. The length of the field vectors was scaled logarithmically as $K\ (1 + \log B_{ij})$ where ij = xy or yz, with representative values of 1 and 100 nT (nano tesla) illustrated. The periodic traversal of the current sheet within 80 R_J is immediately evident in the alternating direction of vectors in the X-Y projection.

Those vectors with a positive X component were observed above the current sheet and a negative X component below. Note that the field direction observed in the X-Y plane does not change significantly along the trajectory and indeed approaches a direction, which as the magnetopause is approached, is parallel to the magnetopause.

The X-Z projection shows that close to the planet there is a substantial negative Z component, consistent with the inner magnetosphere being dominated by the planetary dipole term. The field vectors beyond 30 R_J tend to be more parallel to the solar magnetospheric equatorial plane for the most part. However, the field vectors do show an increasingly southward tilt at larger radial distances and at increasingly smaller and also more negative values of the spacecraft Z_{SM} position.

Comparing these data to the Figure 1 diagram in SM coordinates, it is noted that both the orientation of the field at negative SM latitudes and the occurrence of incomplete current sheet crossings is consistent with a current sheet merging with a neutral sheet surface which bends southward at larger distances at this time. It should be emphasized that due to the long transit time from periapsis to first outbound magnetopause crossing, 10 days, some of the variations in the data may reflect temporal variations in the magnetosphere structure. These are convolved with large scale spatial variations, which form the principal subject of this report.

The direction of the field and the position of the current sheet and neutral sheet, as either directly observed or inferred, is quite reminiscent of observations made in the vicinity of the Earth by spacecraft traversing the magnetic tail in the dawn region of the terrestrial magnetosphere. To illustrate this point, Figure 3 presents magnetic field observations from the IMP 1 satellite which discovered the Earth's magnetic tail[8]. This figure shows that near the dawn terminator, the field is distorted from the magnetic meridian planes and is bent backward so as to parallel the magnetopause boundary. Superimposed on this diagram are the trajectories of Voyager 1 outbound and Pioneer 10 assuming equal scaling of the positions of the magnetopauses. The Voyager 1 magnetic field results as shown in the upper panel of Figure 2 are consistent with those to be expected from this figure. It is also seen from this figure that along the Pioneer 10 trajectory, less tailward than Voyager 1, a magnetic tail would still be evidenced. The field orientation would change from the magnetic meridian plane when close to the planet, and become gradually deflected tailwards until an angle of approximately 60^{o} is reached near the dawn terminator, paralleling the magnetopause. This is exactly the behavior observed by the Pioneer 10 magnetic field experiment[4].

The Pioneer 10 observations just inside the magnetopause also showed several complete traversals of the current sheet[4]. This is most readily understood if solar wind control of the outermost regions of the Jovian magnetosphere was the responsible mechanism, rather than an internal process as required by the alternate models. Thus we conclude that, on the basis of Voyager 1 magnetic field observations, a consistent model of the Jovian outer magnetosphere should incorporate the development of an extended magnetic tail with an embedded neutral sheet.

INTERPRETATIONS AND IMPLICATIONS

The observations of the positions of the outbound magnetopause crossings imply a magnetic tail radius of 300-400 R_J, if the tail is assumed to be roughly circular. Shown in Figure 4 is a sketch portraying the distortion of the magnetic field in the current sheet region in the inner magnetosphere and the merging of the magnetodisk current sheet with the neutral sheet of the magnetic tail in the outer magnetosphere. This diagram is based primarily upon an analogy with terrestrial magnetosphere studies and is adapted for Jupiter by showing a much larger distension of the magnetic field lines near the current sheet. Jupiter also presents a smaller angle of attack for the solar wind, relative to the magnetic equatorial plane of Jupiter, because of the small obliquity to the ecliptic of the Jovian rotation axis ($\sim 3^{o}$). Nonetheless, the observed curvature of the neutral sheet and current sheet observed by Voyager 1 in the outbound traversal imply a three dimensional geometry so that the tail is not symmetric about the neutral sheet. We expect that Voyager 2, which will pass further down the magnetic tail, will provide additional insight on the structure of the Jovian magnetosphere, especially the outer portion.

As at Earth, it can be assumed that the magnetic field in the magnetic tail connects to the polar cap regions in order to estimate the size of the polar cap region itself. Figure 5 presents a comparison of tail field observations near the magnetopause by Voyager 1 and Pioneer 10 with theoretical models which assume a polar cap radius of 8^o, 10^o and 13^o. For this computation, it is assumed that only the planetary magnetic dipole term is responsible for the total flux connecting to the magnetic tail. As seen in Figure 5, Voyager 1 and Pioneer 10 suggest a polar cap auroral zone of $10^o \pm 1^o$. This is substantially smaller than Earth's, which is approximately 18^o to 22^o. This is also much smaller than the polar cap region inferred at Mercury by the same analysis, approximately 18^o - 26^o.

Earth's magnetic tail field is known to decrease significantly in magnitude down the tail and to vary in time due to changing solar wind and internal magnetospheric conditions. It is not possible from the limited data presently available at Jupiter to determine whether or not the same analytical form is valid. However, due to probable merging across the neutral sheet and flaring of the magnetopause boundaries, the field intensity in the Jovian tail is expected to decrease significantly tailward and indeed, the Voyager 1 (3 nT) and Pioneer 10 (5 nT) observations show this to be true.

The implication of the existence of a magnetic tail, with respect to the polar cap region, can be further studied by determining more precisely the location of the polar cap auroral zones. While this cannot be done for an exact model of the Jovian magnetosphere, a reasonable approximation can be made. The equivalent dipole co-latitude has been computed to equate the polar cap flux to the total flux in the magnetic tail. With these values, we then trace the magnetic field lines from the equator at those radial distances corresponding to 8^o and 13^o using the GSFC O_4 planetary magnetic field representation, including quadrupole and octupole terms, but neglecting external currents. The auroral zones so derived are shown in Figure 6.

The small size of the zones is immediately evident as is a surprisingly large eccentricity of the northern polar cap. The asymmetric position of the oval is due to the specific multipole characteristics of the planetary field while its size is determined by the number of field lines required to connect to the total flux in the magnetic tail. Also shown are the footprints of the Io fluxtube, which map out the position of the Jovian line of force which threads the satellite Io as it orbits the planet. It has been known for sometime that the relative position of the satellite Io is related to the probability of observing decametric emission from the Jovian polar regions[10]. Although a specific mechanism has not yet been developed for explaining these emissions, there is now reasonably good agreement between the maximum frequencies expected (39.0 MHz) based upon the observed maximum magnetic field intensity (14.0 Gauss) and the observed maximum frequency (39.5 MHz), assuming emission at the electron cyclotron frequency. We point to the uniquely eccentric position of the northern polar cap auroral zone of Jupiter as an important and anomalous feature of the Jovian magnetospheric configuration. Table 1 presents the coordinates of the polar cap auroral zones, assumed dipole co-latitude of 10°, and field magnitude (in Gauss).

SUMMARY

The observations from Voyager 1 taken while the spacecraft exited the magnetosphere of Jupiter in March 1979 show rather convincing evidence of the development of an extended magnetic tail and imbedded neutral sheet in the nightside magnetosphere of Jupiter, which is formed by the solar wind interaction. This indicates substantial external control of the outer magnetosphere of Jupiter rather than only inner control as postulated by the magnetodisk and magnetic anomaly models. The size of the tail inferred (300-400 R_J diameter), and the field intensity measured (3 nT) imply rather smaller polar cap regions at Jupiter than at Earth. The complex planetary magnetic field model GSFC O_4 yields a highly eccentric northern polar cap region, encircling neither rotation axis nor magnetic axis.

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REFERENCES

1. Van Allen, J. A., Baker, D. N., Randall, B. A., Thomsen, M. F., Sentman, D. D. and Flindt, H. F., Science, 188, 459-462, 1974; Smith, E. J., Davis, L. Jr., Jones, D. E., Coleman, P. J. Jr., Colburn, D. S., Dyal, P., Sonett, C. P., and Frandsen, A. M. A., J. Geophys. Res., 79, 3501-3513, 1974.
2. See review by Goertz, C. K., Space Sci. Revs., 23, 319-344, 1979 and references contained therein.
3. Northrop, T. G., Goertz, C. K., and Thomsen, M. F., J. Geophys. Res., 79, 3579-3583, 1974.

   Kivelson, M. G., Coleman, P. J., Froidevanx, L. and Rosenberg, R. L., J. Geophys. Res., 83, 4823-4841, 1978.
4. Smith, E. J., Davis, L. Jr., and Jones, D. E. in Jupiter ed. by T. Gehrels, U. of Arizona, Tucson 1976, pp.788-829.
5. Dessler, A. J. and Vasyliunas, V., Geophys. Res. Lttrs., 6, 37-40, 1979 and references contained therein.
6. Acuna, M. and Ness, N. F., J. Geophys. Res., 81, 2917-2922, 1976.
7. Ness, N. F., Acuna, M. H., Lepping, R. P., Burlaga, L. F., Behannon, K. W., and Neubauer, F. M., Science, 204, 982-987, 1979.
8. Ness, N. F., J. Geophys. Res., 70, 2989-3005, 1965.
9. Ness, N. F., Behannon, K. W., Lepping, R. P. and Whang, Y. C., J. Geophys. Res., 80, 2708-2716, 1975.
10. Carr, T. D. and Desch, M. D., in Jupiter, ed. by T. Gehrels, U. of Arizona, Tucson 1976, pp.693-737.

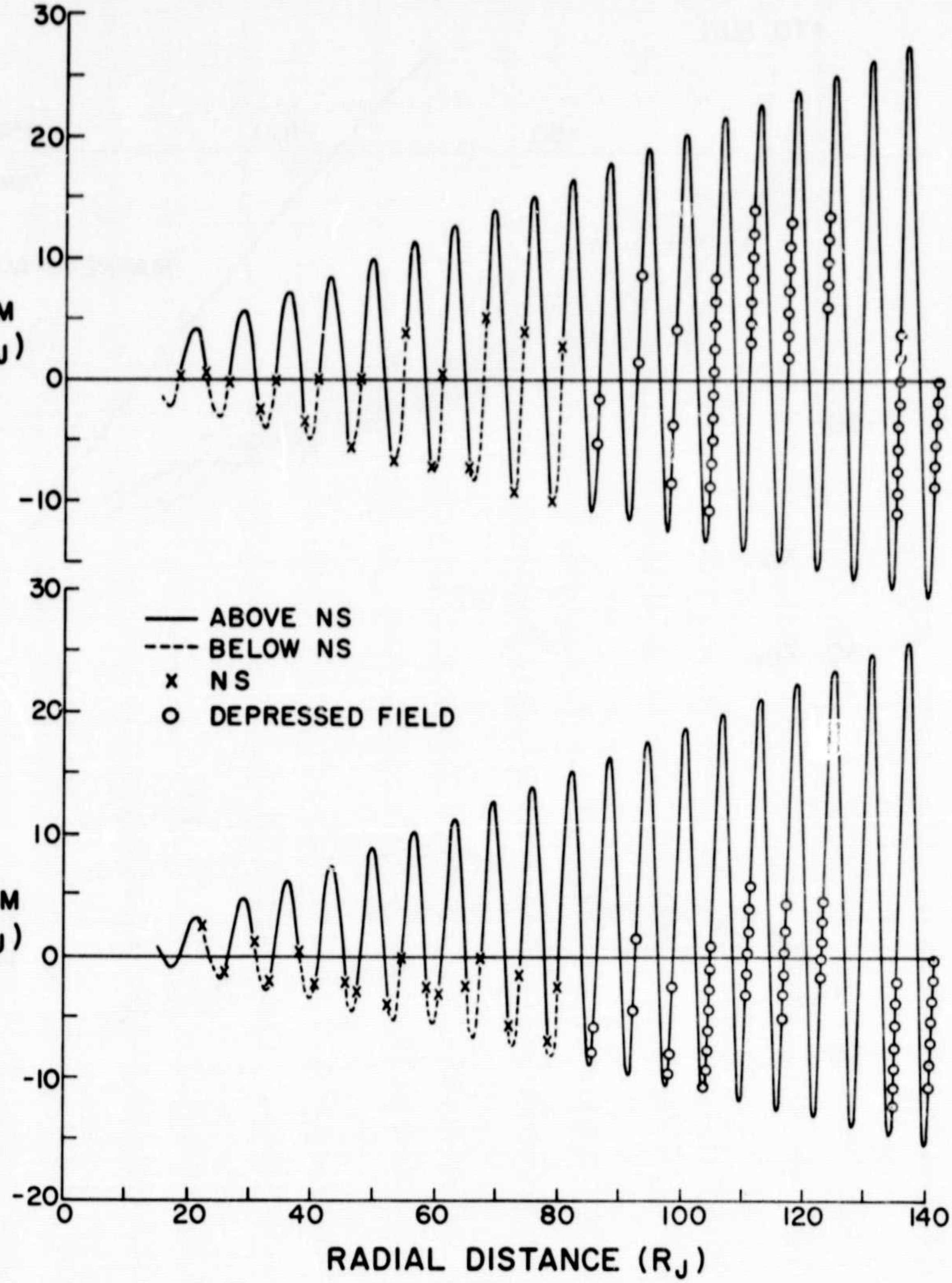
11. We acknowledge useful discussions of these results with our Voyager colleagues, especially C. K. Goertz of the M.I.T. Plasma Science Team.

PREDICTED SYSTEM III (1965) COORDINATES OF JOVIAN AURORAL ZONE

NORTHERN			SOUTHERN		
LATITUDE	LONGITUDE	$\lvert\vec{B}\rvert$	LATITUDE	LONGITUDE	$\lvert\vec{B}\rvert$
+81.2°	+143.4°	10.8	-77.3°	8.4°	9.1
+80.6°	+180.4°	10.3	-78.0°	336.7°	9.8
+73.9°	+190.2°	10.6	-80.5°	306.4°	10.2
+67.0°	+184.1°	11.5	-84.2°	261.5°	10.2
+62.7°	+174.2°	12.5	-84.5°	177.7°	10.0
+61.9°	+163.0°	13.2	-79.9°	128.9°	9.6
+64.4°	+151.3°	13.3	-76.1°	102.6°	9.1
+69.5°	+140.0°	12.8	-75.3°	78.1°	8.6
+75.7°	+132.8°	11.8	-76.6°	45.8°	8.6

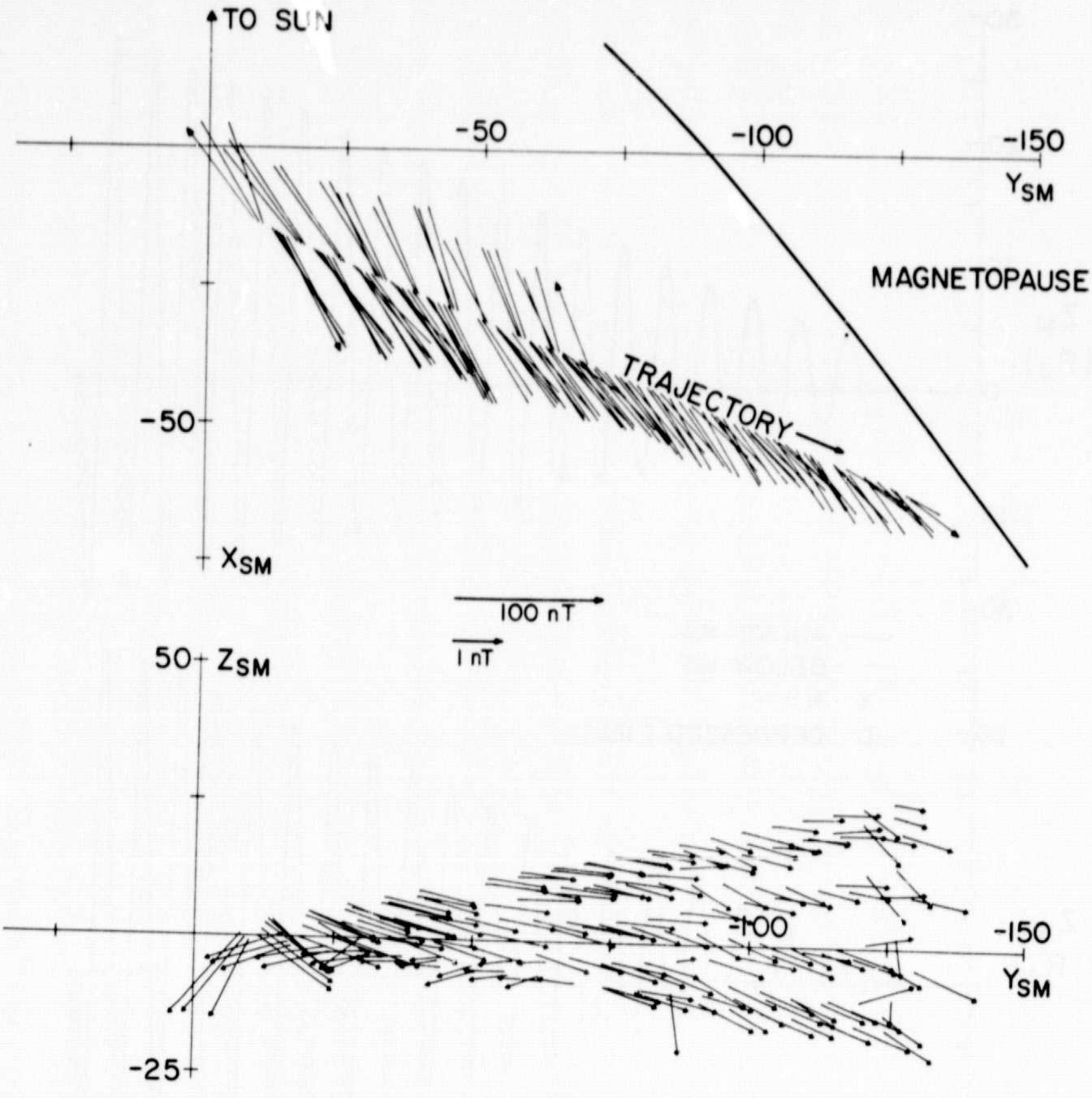
TABLE 1

LIST OF FIGURES



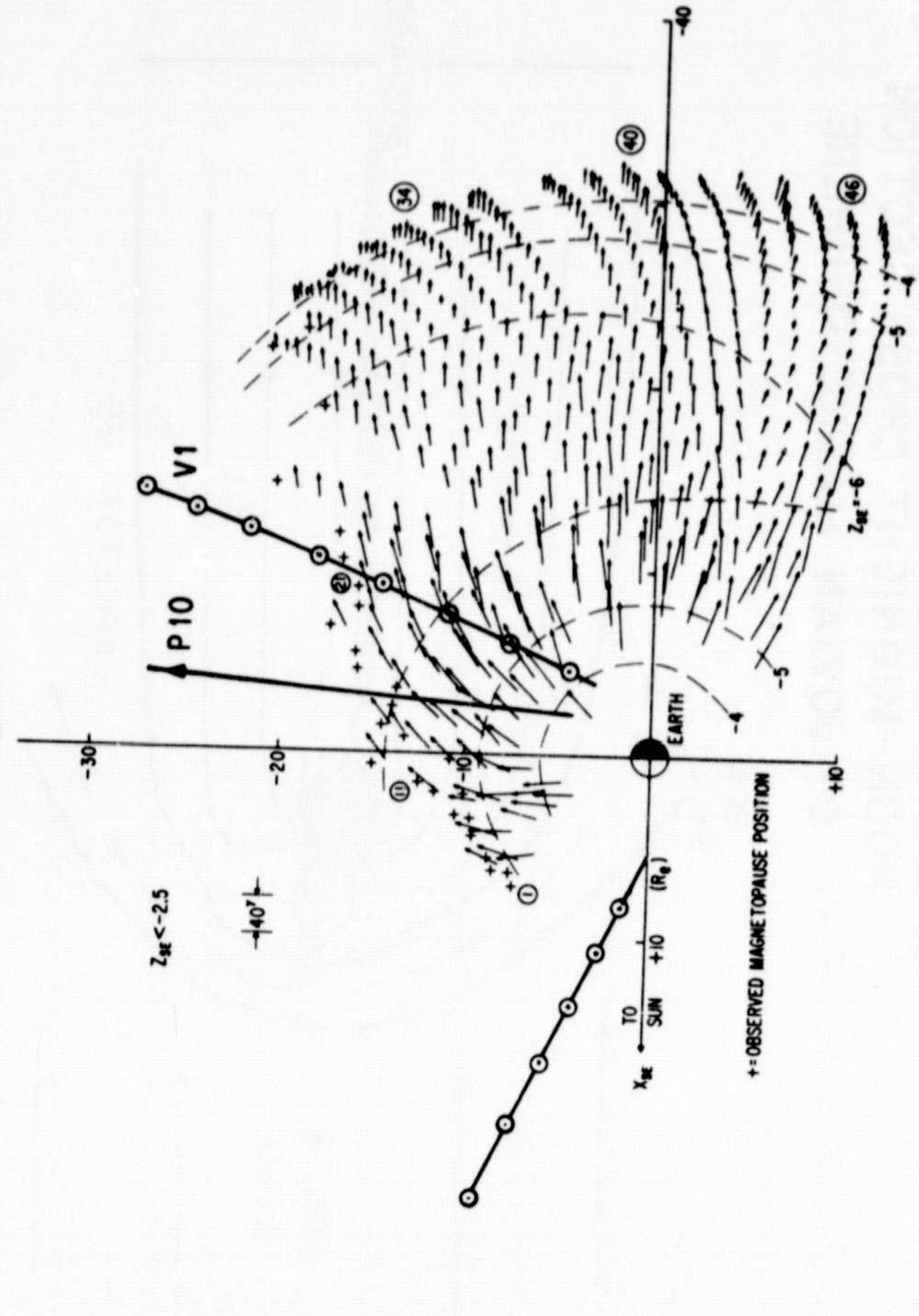
30
20
10
0
-10
Z_M
(R_J)
30
20
10
0
-10
-20
Z_{SM}
(R_J)
ABOVE NS
BELOW NS
NS
DEPRESSED FIELD
0
20
40
60
80
100
120
140
RADIAL DISTANCE (R_J)

FIGURE 1



TO SUN
-50
-100
-150
Y_{SM}
MAGNETOPAUSE
TRAJECTORY
-50
X_{SM}
100 nT
1 nT
50
Z_{SM}
-100
-150
Y_{SM}
-25

FIGURE 2



$X_{SE}-Y_{SE}$ COMPONENT OF MAGNETOSPHERE FIELD

RESULTS FROM IMP-1 (11/27/63-5/31/64)

FIGURE 3

NOON-MIDNIGHT CROSS SECTION OF JOVIAN MAGNETOSPHERE

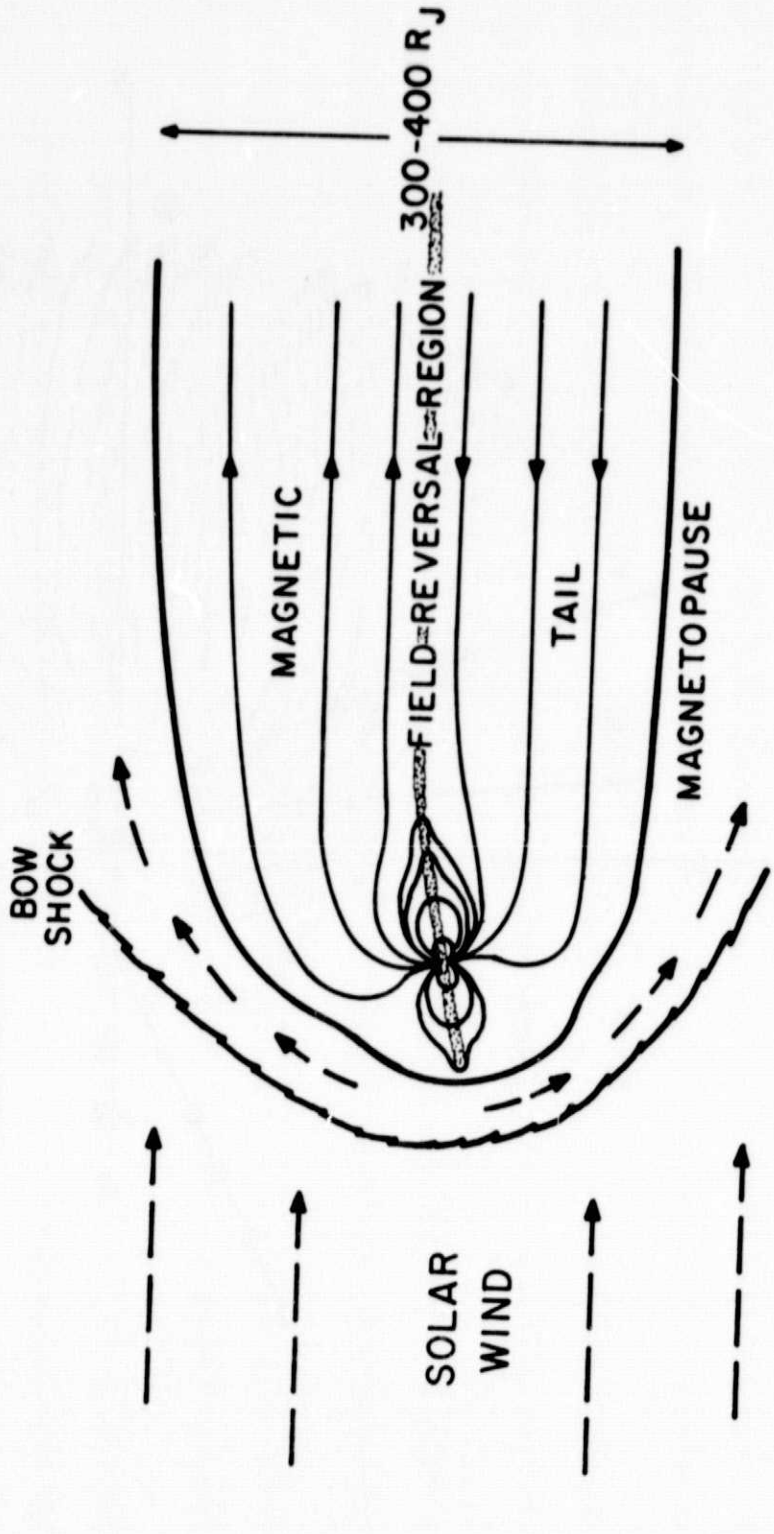
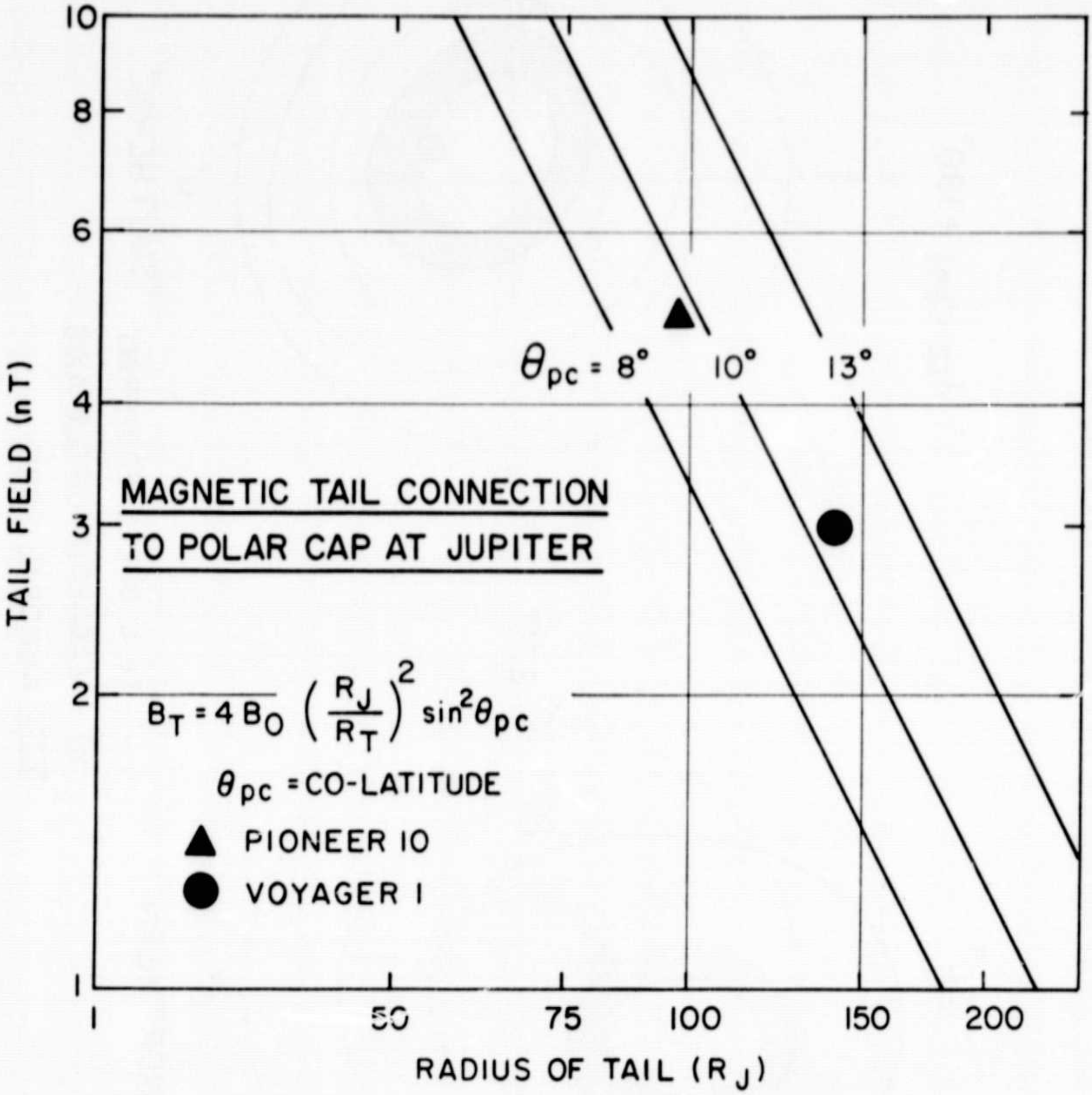
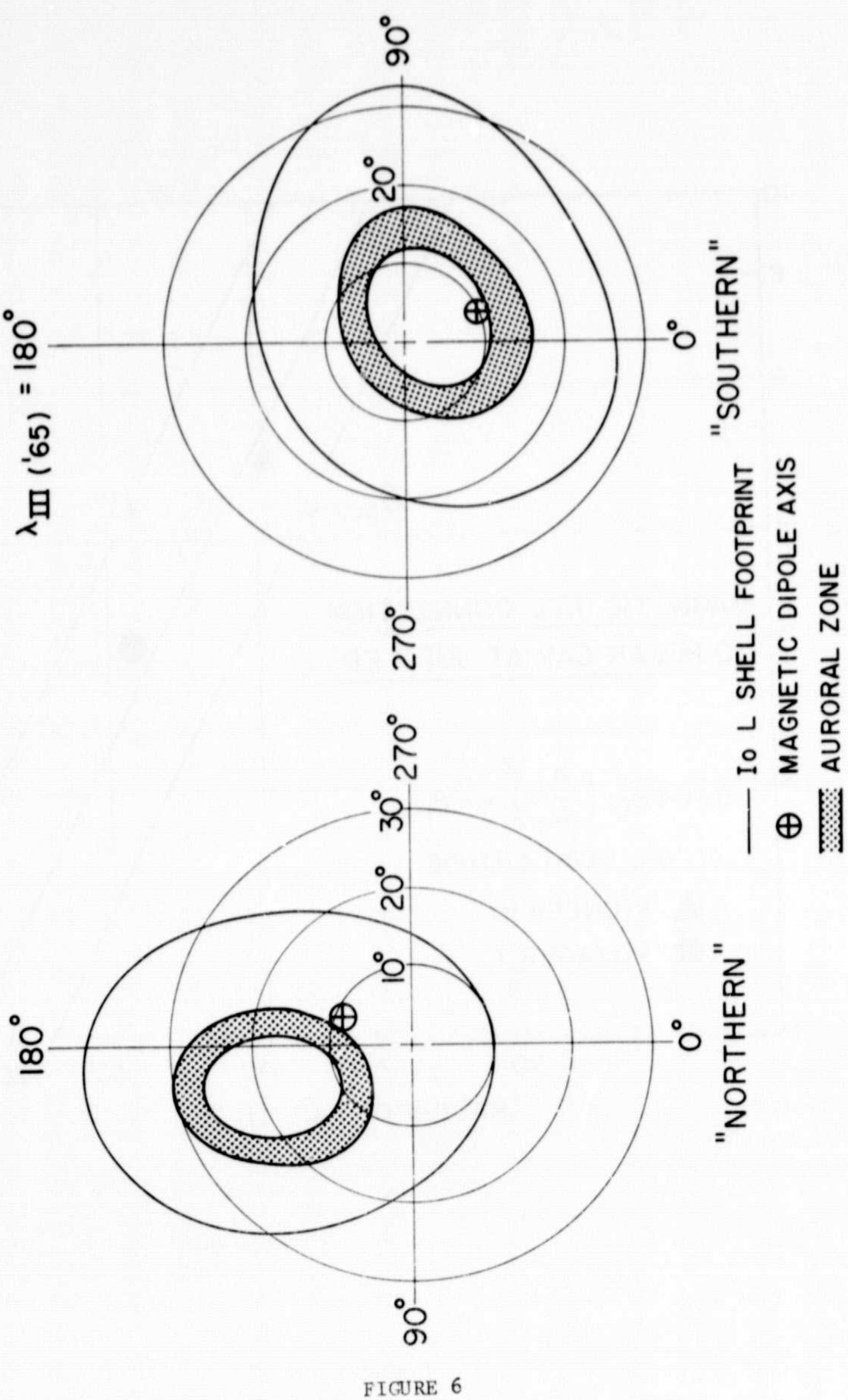


FIGURE 4



10
8
6
4
3
2
1
TAIL FIELD (nT)
θ_{pc} = 8°
10°
13°
MAGNETIC TAIL CONNECTION
TO POLAR CAP AT JUPITER
$B_T = 4 B_O \left(\frac{R_J}{R_T}\right)^2 \sin^2\theta_{pc}$
θ_{pc} = CO-LATITUDE
PIONEER 10
VOYAGER 1
1
50
75
100
150
200
RADIUS OF TAIL (R_J)

FIGURE 5



λ_III ('65) = 180°
180°
90°
0°
270°
10°
20°
30°
"NORTHERN"
90°
270°
0°
20°
"SOUTHERN"
Io L SHELL FOOTPRINT
MAGNETIC DIPOLE AXIS
AURORAL ZONE

FIGURE 6

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